



## H.E.S.S. observations of the supernova remnant RCW 86

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**Abstract:** The shell-type supernova remnant (SNR) RCW 86 - possibly associated with the historical supernova SN 185 - was observed during the past three years with the High Energy Stereoscopic System (H.E.S.S.), an array of four atmospheric-Cherenkov telescopes located in Namibia. The multi-wavelength properties of RCW 86, e.g. weak radio emission and North-East X-ray emission almost entirely consisting of synchrotron radiation, resemble those of two very-high energy (VHE;  $> 100$  GeV)  $\gamma$ -ray emitting SNRs RX J1713.7-3946 and RX J0852-4622. The H.E.S.S. observations reveal a new extended source of VHE  $\gamma$ -ray emission. The morphological and spectral properties of this new source will be presented.

## Introduction

Shell-type supernova remnants are widely believed to be the prime candidates for accelerating cosmic rays up to  $10^{15}$  eV. The most promising way of proving the existence of high energy particles accelerated in SNR shells is the detection of VHE  $\gamma$ -rays produced in nucleonic interactions with ambient matter. Recently, the H.E.S.S. instrument has detected VHE  $\gamma$ -ray emission from two shell-type SNRs, RX J1713.7-3946 [3] and RX J0852.0-4622 [1]. They both show an extended morphology highly correlated with the structures seen in X-rays. Although a hadronic origin is highly probable in the above cases, a leptonic origin can not be ruled out.

Another young shell-type SNR is RCW 86 (also known as G315.4-2.3 and MSH14-63). It has a complete shell in radio [9], optical [12] and X-rays [10], with a nearly circular shape of 40' diameter. It received substantial attention because of its possible association with SN 185, the first historical galactic supernova. However, strong evidence for this connection is still missing: using optical observations, Rosado et al. [11] found an apparent kinematic distance of 2.8 kpc and an age of 10 000 years, whereas recent observations of the North-East part of the remnant with the Chandra and XMM-Newton satellites strengthen the case

that the event recorded by the Chinese was a supernova and that RCW 86 is its remnant [14]. These observations also reveal that RCW 86 has properties resembling the already established TeV emitting SNRs mentioned above: weak radio emission and X-ray emission (almost) entirely consisting of synchrotron radiation, which could be due to the expansion of the shock in a wind blown bubble. The South-Western rim seems to be completely different, with hard X-ray emission, observed by ROSAT [6], mainly coming from stellar ejecta possibly interacting with circumstellar layers ejected before the SN explosion. The relatively large size of the remnant - about 40' in diameter - and the observation of non-thermal X-rays make it a promising target for  $\gamma$ -ray observations, aiming at increasing the currently modest number of remnants where the shells are resolved in VHE  $\gamma$ -rays. Hints for  $\gamma$ -ray emission from RCW 86 were seen with the CANGAROO-II instrument [16], but no firm detection was claimed. Here, we present recent data on RCW 86 obtained with the full H.E.S.S. array in 2005 and 2006.

## The H.E.S.S. detector and the analysis technique

H.E.S.S. is an array of four imaging Cherenkov telescopes located 1800 m above sea level in the Khomas Highlands in Namibia [8]. Each telescope has a tessellated mirror with an area of 107 m<sup>2</sup> [5] and is equipped with a camera comprising 960 photomultipliers [13] covering a field of view of 5° diameter. Due to the effective rejection of hadronic showers provided by its stereoscopy, the complete system (operational since December 2003) can detect point sources at flux levels of about 1% of the Crab nebula flux near zenith with a statistical significance of  $5\sigma$  in 25 hours of observation [2]. This high sensitivity, the angular resolution of a few arc minutes and the large field of view make H.E.S.S. ideally suited for morphology studies of extended VHE  $\gamma$ -ray sources.

The data on RCW 86 were recorded in runs of typically 28 minutes duration in the so-called “wobble mode”, where the source is slightly offset from the center of the field of view. As a cross-check, the obtained data were analysed using two independent analysis chains, which share only the raw data. The first one is based on the combination of a semi-analytical shower model and a parametrisation based on the moment method of Hillas to yield the combined likelihood of the event being initiated by a  $\gamma$ -ray [7]. We will call this method the “Combined Model analysis” in the following. The second analysis method is the standard stereoscopic analysis based on the Hillas parameters of the shower images [4].

## H.E.S.S. results

RCW 86 was observed for about 30 hours with the H.E.S.S. instrument with a mean zenith angle of 41°. Within a circular region of 27' radius (defined a priori so that it encompasses the whole remnant) around the centre of the SNR ( $\alpha_{J2000} = 14^h42^m43^s$ ,  $\delta_{J2000} = -62^\circ29'$ ), a clear VHE  $\gamma$ -ray signal with more than 9 standard deviations is detected with both analysis methods described above. The exact morphology of the gamma-ray emission is still under study: whereas one type of data analysis shows hints of a 3/4 shell re-

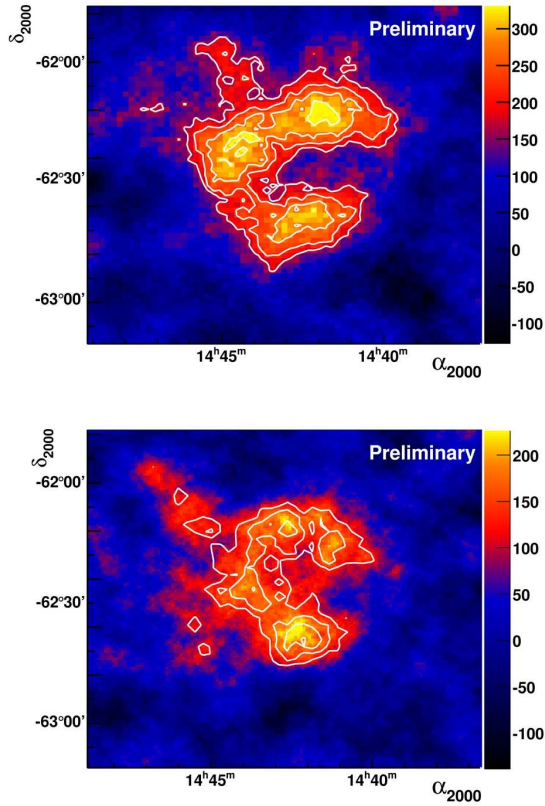


Figure 1: VHE  $\gamma$ -ray emission from RCW 86, as seen with H.E.S.S.. The top image shows the excess skymap obtained with the Combined Model analysis where shower images are matched against image templates, whereas the bottom image results from the classical, slightly less sensitive Hillas analysis technique. White contours correspond to 3, 4, 5, 6 sigma significance, obtained by counting gamma rays within  $0.11^\circ$  from a given location.

sembling the shape of the X-ray emission (Fig. 1 top, Fig 2), this morphology is not quite as evident with the other analysis technique (Fig. 1 bottom), and more data may be required to fully settle this issue. The differential energy spectrum of RCW 86,  $\phi(E)$ , was extracted from a circular region of diameter 22' around the position  $\alpha_{J2000} = 14^h42^m12^s$ ,  $\delta_{J2000} = -62^\circ24'$  which is – different from the region for which the detection significance was determined – adjusted to the H.E.S.S. data to include  $\sim 90\%$  of the  $\gamma$ -ray excess. It is

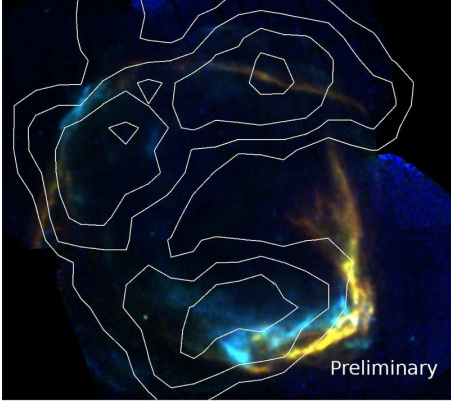


Figure 2: Significance contours of gamma-ray emission (from the Combined Model analysis; 3, 4, 5, 6 sigma) superimposed onto the XMM X-ray image of the remnant [14].

well described by a power-law with a spectral index of  $\Gamma = 2.5 \pm 0.1_{\text{stat}}$  and a flux normalisation at 1 TeV of  $\phi(1\text{TeV}) = (2.71 \pm 0.35_{\text{stat}}) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ . The integral flux in the energy range 1 - 10 TeV is  $\sim 8\%$  of the integrated flux of the Crab nebula within the same range. However, at this level of data statistics, a power-law with index  $\Gamma \sim 1.9$  and an exponential cut-off at  $E_c^\gamma \sim 5 \text{ TeV}$  is also a good fit to the data.

## Discussion

There are two basic mechanisms for  $\gamma$ -ray production in young supernova remnants, inverse Compton scattering of high energy electrons off ambient photons (leptonic scenario) and  $\pi^0$  mesons produced in inelastic interactions of accelerated protons with ambient gas decaying into  $\gamma$ -rays (hadronic scenario). The measured  $\gamma$ -ray flux spectrum from RCW 86 translates into an energy flux between 2 and 10 TeV of  $3.4 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1}$ . In a leptonic scenario, the ratio of this energy flux and the X-ray flux between 2 and 10 keV ( $1.7 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$ , see Winkler [17]) determines the magnetic field to be close to  $22 \mu\text{G}$ . This value, completely independent of the distance and age of the SNR, is compatible with the calculation made by J. Vink et al. [14] based on the thin filaments resolved by Chandra for a dis-

tance of 2.5 kpc in which he also deduces a high speed of the blast wave ( $\sim 2700 \text{ km s}^{-1}$ ). However, it is more than ten times lower than the value proposed by H. J. Voelk and his colleagues [15] for the same distance using a much lower velocity of the shock of  $800 \text{ km s}^{-1}$  as suggested by optical data in the Southern region of the SNR [11].

In a hadronic scenario, one can estimate the total energy in accelerated protons  $W_p$  in the range 10 - 100 TeV required to produce the  $\gamma$ -ray luminosity  $L_\gamma$  observed by H.E.S.S. using the relation:

$$W_p(10 - 100\text{TeV}) \approx \tau_\gamma \times L_\gamma(1 - 10\text{TeV}) \quad (1)$$

in which  $\tau_\gamma \approx 4.4 \times 10^{15} \left(\frac{n}{1 \text{ cm}^{-3}}\right)^{-1}$  is the characteristic cooling time of protons through the  $\pi^0$  production channel. The corresponding  $L_\gamma$  can be calculated using:

$$\begin{aligned} L_\gamma(1 - 10 \text{ TeV}) &= 4\pi D^2 \int_{1 \text{ TeV}}^{10 \text{ TeV}} E \phi(E) dE \\ &= 2.8 \times 10^{31} \left(\frac{D}{200 \text{ pc}}\right)^2 \text{erg s}^{-1} \end{aligned}$$

Finally, the total energy injected in protons is calculated by extrapolating the proton spectrum with the same spectral shape as the photon spectrum down to 1 GeV. Therefore, this estimation is highly dependent on the shape of the  $\gamma$ -ray spectrum. Assuming that the proton spectrum is a power-law with index  $\Gamma = 2.5$ , one would obtain a total energy injected into protons of  $W_p(\text{tot}) = 3 \times 10^{51} \left(\frac{D}{2.5 \text{ kpc}}\right)^2 \left(\frac{n}{1 \text{ cm}^{-3}}\right)^{-1} \text{erg}$ . For densities of  $\sim 1 \text{ cm}^{-3}$ , the only way to explain the entire  $\gamma$ -ray flux by proton-proton interactions in a homogeneous medium is to assume that RCW 86 is a close supernova remnant ( $\sim 1 \text{ kpc}$ ). Indeed, for larger distances and a typical energy of the supernova explosion of  $10^{51} \text{ erg}$ , the acceleration efficiency would be excessive. For an exponential cut-off power-law with  $\Gamma = 1.9$  and  $E_c = 10 \times E_c^\gamma = 50 \text{ TeV}$ , the total energy injected into protons would be  $10^{50} \left(\frac{D}{2.5 \text{ kpc}}\right)^2 \left(\frac{n}{1 \text{ cm}^{-3}}\right)^{-1} \text{erg}$  which would make the hadronic scenario possible even at larger distances. However, the observation of TeV gamma-rays from the remnant up to more than 10 TeV favors somewhat the scenario of a young - and therefore close-by - remnant with high expansion speed, easing the acceleration of high-energy particles.

## Summary

H.E.S.S. observations have led to the discovery of the shell-type SNR RCW 86 in VHE  $\gamma$ -rays. The  $\gamma$ -ray signal is extended but the exact morphology of the emission region is still under study. The flux from the remnant is  $\sim 8\%$  of the flux from the Crab nebula, with a similar spectral index of 2.5, but the spectrum is also well described by a power law with index 1.9 and a cutoff around 5 TeV. The question of the nature of the particles producing the  $\gamma$ -ray signal observed by H.E.S.S. was also addressed. However, at present, no firm conclusions can be drawn from the spectral shape.

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